Seasonal and Interannual Variations of Residence (Flushing) Time in the West Bay of Budd Inlet

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Introduction

We were interested in the seasonal and interannual changes in the flushing time of the West Bay in Budd Inlet due to the low levels of dissolved oxygen (DO) often found near the bottom of the turning basin in the late summer. The Washington State Dept. of Ecology took hydrographic data in the inlet during 1992–4 (Figure 1). We constructed a two-layer box model (Figure 2) and used conservation of mass and salt to calculate overall transports between boxes using these data.

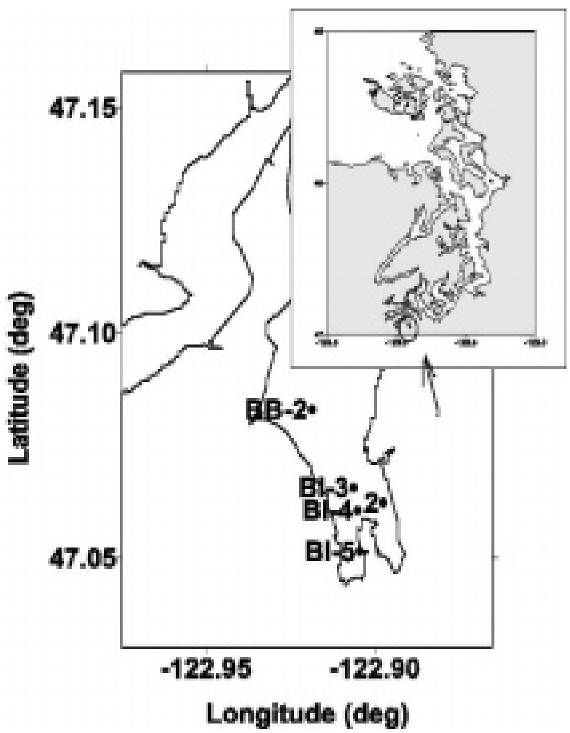


Figure 1. Station locations for box model.

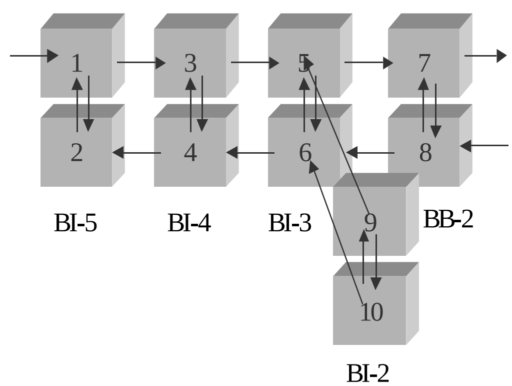


Figure 2. Budd Inlet box model.

Methods

A Volumetric Argument

The Lacey Olympia Tumwater Thurston (LOTT) wastewater treatment plant (WWTP) has a mean summer discharge of about 9 mgd (34,000 m^3/d). The typical outflow from Capital Lake is 475,000 m^3/d; an extreme flow condition is about 1.5 x 10^6 m^3/d. Assuming that all waters mix completely, point "A" (Figure 3, 0.2 km from head) is the location at which the fresh water outflow (river plus LOTT) is equal to the volume of the tidal exchange (top - bottom curve) under typical conditions. This is the distance from the head of the inlet where 50% dilution of fresh water outflow with saltwater occurs in one day. Consequently, the turning basin, which is approximately 0.6 km from the head of the inlet (point "B"), should flush in about one-third of a day based on this tidal advection and thorough mixing. In the extreme flow condition, this flushing time increases to about one day at the turning basin.

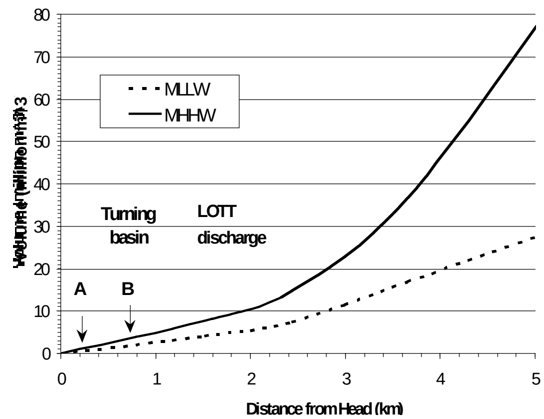


Figure 3. Water volume vs. distance from the head of Budd Inlet at Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW).

Box Models and the Knudsen Relation

Unlike the scenario above, we know the actual state of mixing in an estuary is apt to be less than thorough. In the absence of current meter data, the box model solution is uniquely determined and reduces to the Knudsen relationship (Knudsen, 1900) solution at any single location. The box model, however, allows determinations of both horizontal and vertical transports, as well as inclusion of multiple freshwater sources at different locations. Ideally, station locations should be chosen with a box model in mind, if that is to be the purpose. We, however, chose from available monitoring stations and accepted or rejected them as suitable for our purpose. Although station BI-3 (Figure 1) was shallow, 9 m east of the main channel, it nevertheless received a good freshwater signal and was included in the model. However, fluxes into and out of the bottom box at this location (box 6) should be ignored.

We made the following assumptions (justifications not shown):

- Steady-state (no change with time)
- Two-layer tidally averaged flow
- Only freshwater sources: Capital Lake (Deschutes), Moxlie & LOTT WWTP
- Each box is homogeneous
- Negligible evaporation/precipitation

Only surveys that included both high and low tide transects were used, and those data were averaged from the surface down (i.e., salinities from the top 2.5 m from the low tide was averaged with the top 2.5 m from the high tide). Without current meter data we could not establish the level of "no motion" and instead used the average depth of the halocline, 2.5 m, as the separation depth between top and bottom boxes in the model (Figure 4).

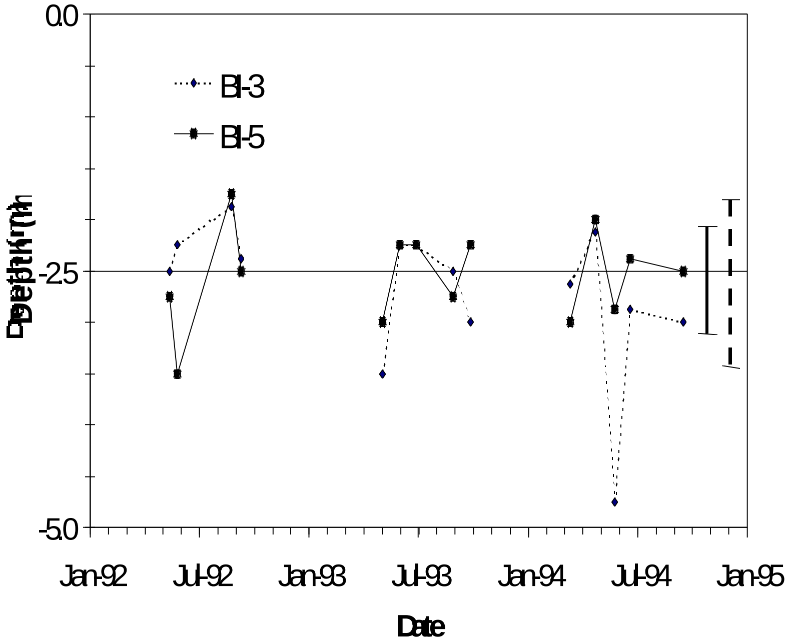


Figure 4. Halocline depths at two stations.

River flows, which were not at all steady, were smoothed forward and backward half a sidereal day. On the average, along-channel vertical transects of salinity showed the typical estuarine flow pattern with a slight downstream shift of the freshwater maximum (Figure 5). Thus in our box model results, the flows from the bottom, innermost box may be inaccurate.

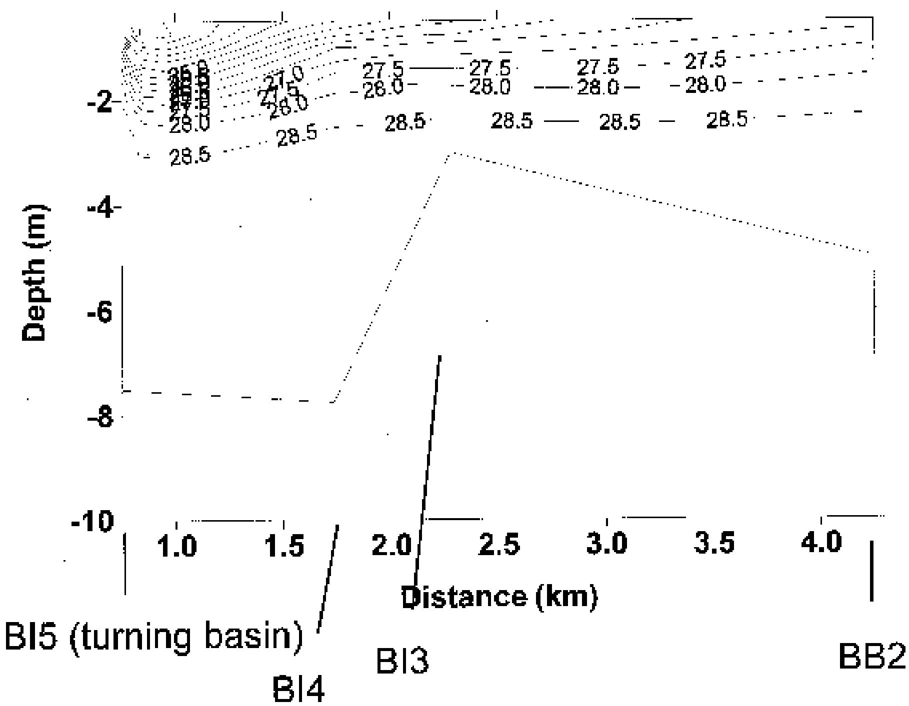
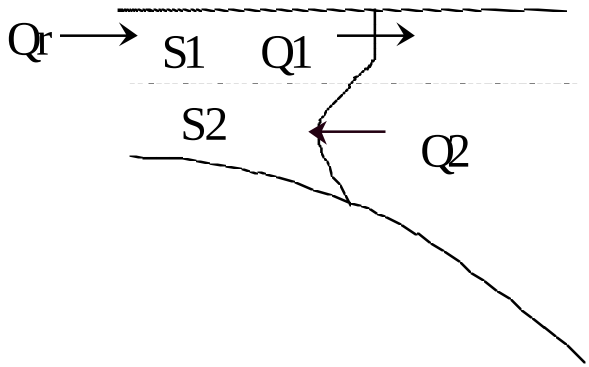


Figure 5. Vertical profile of mean salinity (psu) for all surveys included in the model Knudsen relation in the turning basin.

Stratification that persists with (seasonal) reductions of freshwater discharge is indicative of poor flushing conditions. The Knudsen relation quantifies this at one station as:

$$\Delta S = S_2 - S_1$$
$$\tau_1 = V_1\, \Delta S \,/\, Qr\, S_2$$
$$\tau_2 = V_2\, \Delta S \,/\, Qr\, S_1$$



where:

- Qr is the freshwater inflow
- S_1 & Q_1, S_2 & Q_2 are the surface and bottom salinities and flows, respectively
- V_1 & V_2 are the surface and bottom box volumes
- and τ_1 & τ_2 are the derived residence times.

In order to see the flows between stations, we constructed a box model whose solution is found by solving the matrix in Figure 6.

Conservation of mass: (rows 1–10)

Conservation of salt: (rows 11–20)

$$\left[\begin{array}{cccccccccccccccccccc}
1 & -1 & 1 & & & & & & & & & & & & & & & & & \\
-1 & 1 & & -1 & & & & & & & & & & & & & & & & \\
 & & -1 & & 1 & -1 & 1 & & & & & & & & & & & & & \\
 & & & 1 & -1 & 1 & & -1 & & & & & & & & & & & & \\
 & & & & & & -1 & & 1 & -1 & 1 & & & & & & & & -1 & \\
 & & & & & & & 1 & -1 & 1 & & -1 & & & & & & & & 1 \\
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 & & & & & & & & & & & 1 & -1 & 1 & & -1 & & & & \\
 & & & & & & & & & & & & & & & & 1 & -1 & 1 & \\
 & & & & & & & & & & & & & & & & -1 & 1 & & -1 \\
S_1 & -S_2 & S_1 & & & & & & & & & & & & & & & & & \\
-S_1 & S_2 & & -S_4 & & & & & & & & & & & & & & & & \\
 & & -S_1 & & S_3 & -S_4 & S_3 & & & & & & & & & & & & & \\
 & & & S_4 & -S_3 & S_4 & & -S_6 & & & & & & & & & & & & \\
 & & & & & & -S_3 & & S_5 & -S_6 & S_5 & & & & & & & & -S_9 & \\
 & & & & & & & S_6 & -S_5 & S_6 & & -S_8 & & & & & & & & S_6 \\
 & & & & & & & & & & -S_5 & & S_7 & -S_8 & S_7 & & & & & \\
 & & & & & & & & & & & S_8 & -S_7 & S_8 & & -S_{12} & & & & \\
 & & & & & & & & & & & & & & & & S_9 & -S_{10} & S_9 & \\
 & & & & & & & & & & & & & & & & -S_9 & S_{10} & & -S_6
\end{array}\right]
*
\left[\begin{array}{c}
q_{1,2} \\ q_{2,1} \\ q_{1,3} \\ q_{4,2} \\ q_{3,4} \\ q_{4,3} \\ q_{3,5} \\ q_{6,4} \\ q_{5,6} \\ q_{6,5} \\ q_{5,7} \\ q_{8,6} \\ q_{7,8} \\ q_{8,7} \\ q_s \\ q_b \\ q_{9,10} \\ q_{10,9} \\ q_{9,5} \\ q_{6,10}
\end{array}\right]
=
\left[\begin{array}{c}
q_r \\ 0 \\ q_l \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ q_m \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{array}\right]
\begin{array}{l}
\text{Capital lake outflow} \\ \\ \text{LOTT discharge} \\ \\ \\ \\ \\ \\ \text{Moxlie creek outflow} \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\
\end{array}$$

Figure 6. The box model (q_s = surface flow out of Box 7, q_b = bottom flow into Box 8).

Results

From the Knudsen relation, we find that despite seasonal downturns in freshwater inflow (Qr), the stratification (ΔS) remains fairly high, indicating longer residence times in the turning basin (Figure 7). The largest residence time was nearly four days on 19 September 1994 in the bottom of the turning basin.

From the box model, we find that flushing in the turning basin (Box 2) usually occurs in less than one day. The seasonal pattern is consistent for all the stations, with the highest residence times occurring in the late summer. The interannual variation shows the highest residence times occurring in the fall of

1994 (Figure 8). This corresponds with when the lowest DO concentrations were observed during the original study (Eisner and Newton, 1997).

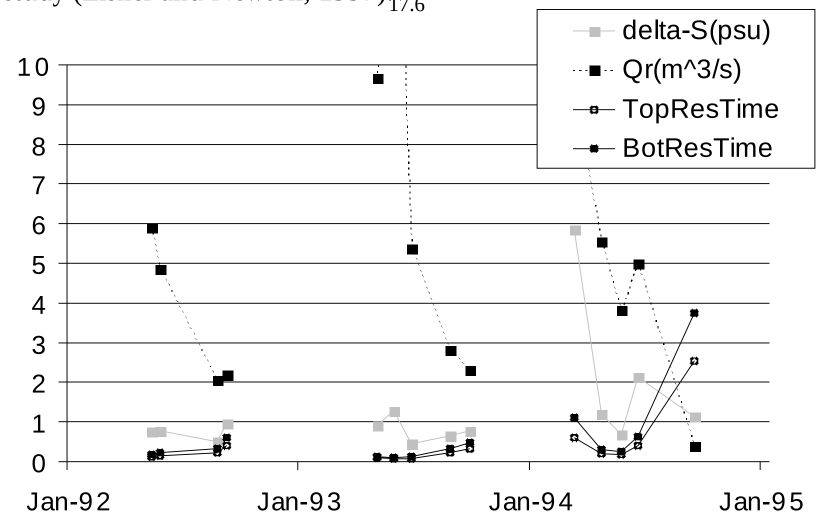

Figure 7. Knudsen relation results in the turning basin (Station BI-5, model Box 2).

Transports and currents in the East Bay are particularly low, but so is the volume. West bay flows were approximately 10 cm/sec in the model, which are comparable to those measured by ADCP (Davis et al., in press). Upwelling was greatest in the box model around station BB-2 at about 310 m^3/sec (Figure 7).

Discussion

At times when fresh water inputs are greatest, the box model predicts flushing times of less than a day; this is consistent with the results from the volumetric argument which assumes thorough mixing. At times when there is less mixing, mainly in the late summer, the residence times increase. The Knudsen relation and the box model solutions have the same seasonal and annual patterns.

The increase in residence times occurs at the same time of the year as the end of the growing season for the inlet, contributing to depressed levels in the dissolved oxygen (DO) concentrations. The highest chlorophyll *a* concentrations occur in the central bay, near station BB-2 (Eisner and Newton, 1997), which is possibly related to the gyre circulation (Ebbesmeyer, this volume). This results in large amounts of carbon falling into the bottom waters and decaying, consuming oxygen in the process, such that the water moving into the turning basin (BI-5) would already have low DO. Coupling this with seasonally high residence times could explain why we find near-hypoxic conditions in the turning basin in the late summer and early fall. The correspondence of the lowest DO concentrations occurring when residence times were greatest (fall, 1994) is consistent with this understanding.

Possible physical mechanisms to account for the seasonal variations in flushing include: lower tidal forcing near the equinox at the end of September (pers. comm., H. Mojfeld, NOAA PMEL), seasonal changes in wind patterns and resultant gyres which may retain water in the basin. The year-to-year variability is more likely linked to changes in weather patterns and river flow (Albertson, 1996).

Acknowledgments

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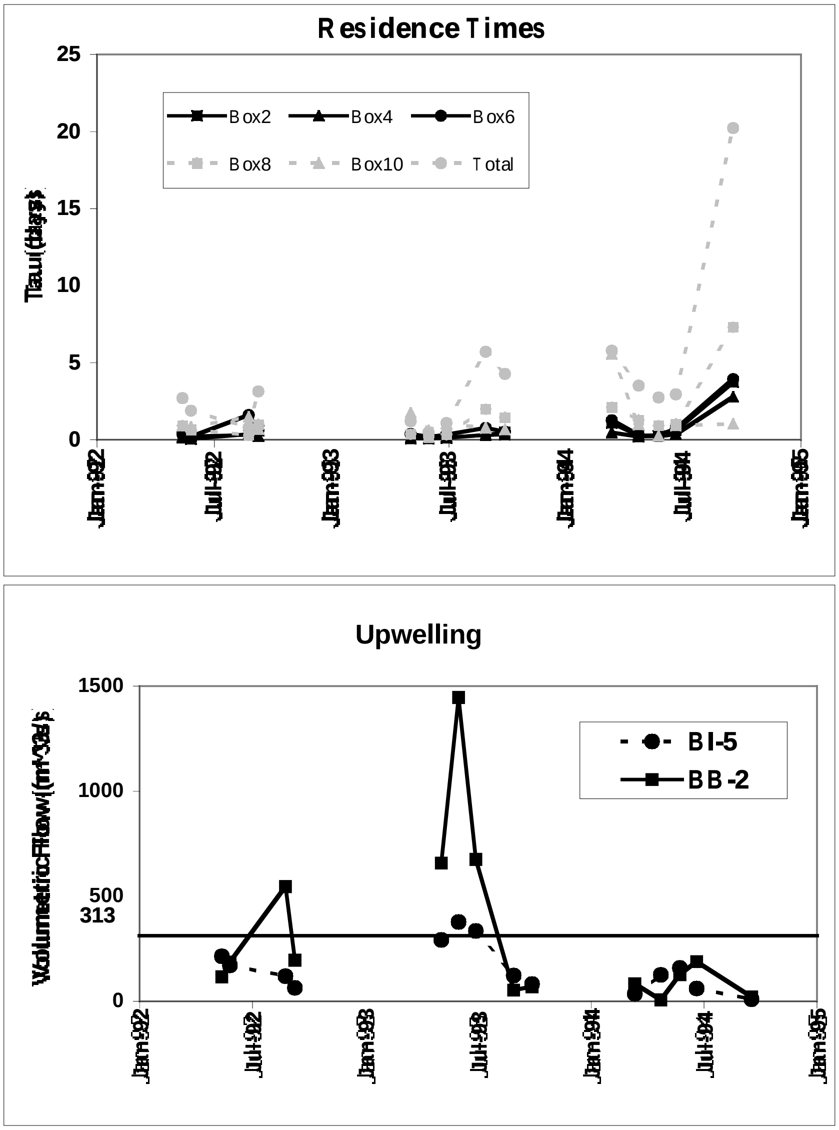

Figure 8. Box model outputs of residence time and vertical transport. The solid line represents a mean upwelling rate of 313 m^3/sec.

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